Reply to: Signatures of sunspot oscillations and their interpretation – a case about chromospheric resonances

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1 Context

In our paper,¹ we studied a fully formed active region that was approximately halfway through its evolutionary lifecycle, with examination of the Fourier-derived spectral energies of the sunspot umbra revealing a spectral ‘bump’ at ≈ 20 mHz. Furthermore, the spectral gradients following the ≈ 20 mHz energy enhancement changed progressively across the umbral diameter, implying they may reflect the intrinsic characteristics of the underlying umbral atmosphere. Numerical simulations of the sunspot atmosphere, harnessing the Lagrangian-Eulerian remap² (LareXd) code, also revealed spectral energy variability at ~ 20 mHz (including changing spectral slopes). These results were consistent with the pioneering theoretical work of Botha et al.³ and Snow et al.,⁴ allowing us to interpret these as a signature of wave resonance arising from the temperature gradients naturally occurring in the solar photosphere and transition region. At the time of publication, we recognised that we had observed strong evidence of resonance behaviour in a single, isolated sunspot structure. As a result, in the Supplementary Information of our paper we openly posed a number of key outstanding questions, and requested that the community examine sunspot wave phenomena on a statistical basis, in order to verify how commonplace resonance signatures are.

The Matters Arising by Felipe⁵ highlights the observational and modelling challenges facing solar physicists in the modern era of high time, spatial, and spectral resolutions. We welcome this particular side of his communication as it directly reflects the open questions we posed in the Supplementary Information of our Letter. Considering our paper, Felipe remarks that: (1) the observational power spectra of sunspots do not always demonstrate consistent signatures that can be used as an indicator for the presence of a resonance cavity; (2) theoretical time series can generate spectral energy enhancements that are not solely linked to resonance effects; and (3) the interplay between linear and non-linear effects are likely to play a role in the features observed in both simulated and observed power spectra. In the following, we address the points raised by Felipe to highlight the importance of ongoing research in this challenging scientific field.

2 He I 10830 Å Sunspot Observations

Felipe highlighted that the observations we presented were ‘extraordinary’. Indeed, the quality of the atmospheric seeing can be estimated by the root mean square (rms) fluctuations required to co-align (on a sub-pixel level) successive image from our time series. For this task, the contemporaneous 4170 Å blue continuum imaging observations obtained with the Rapid Oscillations in the Solar Atmosphere⁶ (ROSA) instrument were employed, as these were acquired with short exposure times (5 ms) to prevent any seeing-induced smearing from affecting the cross-correlations, and the highest cadence (2.11 s after image reconstruction). In total, there were 2468 ROSA frames, spanning 5207.48 s (~ 87 minutes). Figure 1 documents the absolute sub-pixel shifts in both solar N/S and E/W directions, calculated from the cross-correlation coefficients. At a time of ~ 2835 s into the observing sequence there is a degradation of the image quality caused by a passing cirrus cloud. However, the original adaptive optics (AO) lock point was restored once this had completely passed (at ~ 3060 s) and the pointing accuracy continued to be excellent until 5100+ s, when the seeing degraded and we terminated the observations. Based on the raw (sub-pixel) shifts, the rms fluctuations are $0''.070$ and $0''.073$ for the solar E/W and N/S directions, respectively. These rms pointing fluctuations are less than half of our He I 10830 Å pixel sampling ($0''.15$ per pixel), showing the high image stability achieved during our observations.

Figure 1: **The telescope pointing stability achieved on 14 July 2016.** Rigid shifts, in both solar N/S (top) and E/W (middle) directions, required to co-align consecutive ROSA 4170 Å continuum images, acquired contemporaneously with our He I 10830 Å spectra, over the duration of the observations presented in ref.¹ The image-by-image cross-correlation coefficients (lower) are high, a result of solar N/S and E/W rms fluctuations on the order of 0".073, demonstrating excellent seeing conditions. The increased fluctuations seen at times of ~2835 s and ~5100 s are caused by the passing of a thin cirrus clouds, with the latter resulting in the termination of the observing sequence.

Indeed, we believe that the excellent seeing conditions are responsible for the clarity of the heightened spectral energy bump at ~20 mHz. To test this hypothesis, we generated time- and wavelength-dependent point spread functions (PSFs) corresponding to 0".75, 1".00, and 1".50 seeing conditions. The PSFs model the AO residual aberrations at the Dunn Solar Telescope focal plane for the three different seeing conditions. These were obtained from simple closed-loop AO numerical simulations carried out with the PAOLA simulation code.⁷ These PSFs, specific to the He I 10830 Å line, were convolved with the original spectra to degrade its spatial resolution, before re-computing the corresponding spectral energy densities. Figure 2 reveals the importance of seeing conditions when exploring the high-frequency regime, with the secondary bump at ~20 mHz being reduced with 0".75 seeing, barely visible with 1".00 seeing, and completely suppressed with 1".50 seeing conditions. Furthermore, it can be seen from Figure 2 that the steepness of the spectral slope following the dominant peak at ~6 mHz is dependent on the quality of the local seeing conditions, with higher frequency fluctuations being heavily damped (by more than an order-of-magnitude) as the seeing conditions degrade. Therefore, spectral energy spectra showing very steep gradients immediately after the universal ~6 mHz dominant peak may not be suitable for such resonance studies, which require prolonged periods of excellent seeing conditions. Hence, the importance of spatial resolution, which is often intrinsically coupled with the local seeing conditions at the telescope, cannot be overestimated when attempting to isolate and quantify high-frequency wave signals in spectroscopic time series. This may be a factor why the spectral energies depicted by Felipe in his Figure 1 show relatively small enhancements (i.e., small excesses above his calculated 99% confidence levels) at ~20 mHz.

Figure 2: Spectral energies of the original and degraded He I 10830 Å observations. The calculated He I 10830 Å spectral energies of the original data products (upper-left), as well as those degraded by convolving time- and wavelength-dependent PSFs corresponding to 0''.75 (upper-right), 1''.00 (lower-left), and 1''.50 (lower-right) seeing conditions. In each panel the graduated blue-to-pink coloured lines represent spectra derived across the entire sunspot umbral diameter, while the solid black lines represent the average umbral spectral energies. It is clear that reduced image quality, caused by worsening seeing conditions and hence poorer spatial resolution, reduce the clarity of high-frequency fluctuations and promote a more rapid spectral energy decline after the dominant ~ 6 mHz peak.

As a result, we wish to emphasise that we are looking forward to the rise of solar cycle 25, which will hopefully be accompanied by new, even higher quality observations from the National Science Foundation’s Daniel K. Inouye Solar Telescope⁸ (DKIST) that can probe the small-scale spectral energy fluctuations of sunspots with unprecedented precision. As a result, we look forward to higher precision polarimetry, extended periods of excellent seeing conditions, and better spatial resolution, which should be able to tell us whether the sunspot documented in Jess et al. is truly exceptional or not.

3 Numerical Modelling and the Effects of Non-linearities

Felipe provided evidence that different numerical simulation codes can demonstrate spectral enhancements at ~ 20 mHz that are linked to non-linear harmonics of the dominant ~ 6 mHz peak, rather than pure wave resonance. We must stress that the simulations developed for our work were constrained by our observational findings, where a He I 10830 Å rms velocity amplitude was on the order of ≈ 3.5 km/s. Hence, the waveforms present in our observations demonstrated predominantly linear traces, with minimal ‘sawtooth’ structuring that would indicate the presence of developing (non-linear) shocks, which was shown in Figure 2 of ref.¹ However,

whilst our observations contained predominantly linear waveforms ($\text{rms} \approx 3.5 \text{ km/s}$), on occasion we did detect velocity amplitudes rising above $\sim 10 \text{ km/s}$, therefore approaching the local sound speed in these instances. As a result, the effects of borderline non-linearities cannot be entirely excluded from a potential interpretation since steep transitions in velocity space are difficult to resolve with the temporal cadence (14.6 s between spectra) of our observations. This again highlights the importance of upcoming DKIST observations, including the use of instruments such as the Diffraction Limited Near Infrared Spectropolarimeter (DL-NIRSP), which will enable simultaneous two-dimensional spatial mapping of the He I 10830 Å line to be obtained with high polarimetric precision and a spatial resolution as high as $0''.06$ (some 5 times higher than the data presented in our study). The increased polarimetric precision will enable more accurate inversions to be achieved, the greater spatial resolution will enable the precise high-frequency energy structuring of sunspots to be deduced with greater clarity, and the two-dimensional fibre-fed nature of the instrument will allow the entire sunspot to be studied simultaneously.

Additionally, it is worth noting that wave behaviour often demonstrates strikingly different signatures when modelled separately through the assortment of available numerical magnetohydrodynamic (MHD) simulations, including the LareXd, MANCHA,⁹ BiFrost,¹⁰ CO⁵BOLD,¹¹ and MuRAM¹² codes. Each code provides specialist and refined treatment of physics to tackle different problem sets, whether it is related to shock-capturing environments or the investigation of partial ionisation effects. As such, it may come as no surprise that different MHD codes may produce different output signatures when modelling the complex lower solar atmosphere. Indeed, Figure 2 presented by Felipe shows a very sharp decrease in spectral energy at $\sim 15 \text{ mHz}$, by almost an order-of-magnitude, which is not consistent with the more smoothly transitioning spectral energies found in both our observations and models, nor the observations presented by Felipe in his Figure 1.

It is imperative that future research attempts to uncover the physics and numerics that accurately replicate the umbral atmosphere. Recent findings^{13,14} have put forward novel approaches to more accurately model the interaction of the transition region with the surrounding atmosphere, which may help to understand the resonance effects at work in sunspot umbrae. In addition, numerical codes can elect to extract information at either constant temperatures or constant geometric heights. The He I 10830 Å spectral line is formed at $\sim 10\,000 \text{ K}$ ¹⁵ or a geometric height of $\sim 2100 \text{ km}$, so a future examination and comparison of the resulting velocity fluctuations between constant isotherms and atmospheric heights may help shine light on the resonant MHD wave interactions with the solar transition region. With this in mind, it is also important to evaluate whether the resonant signatures (spectral enhancement at $\sim 20 \text{ mHz}$ and the variability of subsequent spectral slopes that map the thickness of the underlying cavity) are visible throughout the resonance cavity at different temperatures and/or geometric heights. Furthermore, the effects of rms velocity amplitudes on their corresponding spectral energies need to be documented in a statistical and thorough manner. For example, how do developing shock fronts, oscillation harmonics, and even shock-induced resonances and refractions^{16,17} effect the ability to extract purely resonant signatures from the associated spectra? As a result, and in agreement with the general findings put forward by Felipe, we believe that more research, development, and benchmarking needs to be undertaken in relation to the numerical MHD codes researchers currently have at their disposal. Understanding the dominant mechanisms at work in the lower solar atmosphere will allow numerical codes to more accurately replicate the underlying physics synonymous with these tenuous layers of the Sun’s atmosphere, and hence better reflect the characteristics manifesting in current and upcoming observational datasets.

4 Final Remarks

Based upon the open questions posed in ref.,¹ Felipe’s work provides important additional observational and modelling results that can help shape the research field linked to waves manifesting in sunspot umbrae. While Figure 1(a) of Felipe’s work may reveal slight spectral energy enhancements at $\sim 20 \text{ mHz}$ that are above his calculated 99% confidence levels, they are not as prominent as those found in our observations. From Figures 1 & 2, we hypothesise that this may be linked to our extraordinary dataset captured through harmonious use of modern instrumentation, excellent seeing conditions, high-order adaptive optics, high-precision polarimetry calibrations, and an efficient ground-based telescope facility. Hence, upcoming DKIST observations are of paramount importance for verifying or refuting the absolute role of wave resonances in sunspot umbrae. We wholeheartedly agree with Felipe that there is the need for more in-depth examinations of wave activity in

modern observations and simulations, which again, is consistent with the open questions we posed in ref.¹

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